Orbital Migration of Protoplanets in a Marginally Gravitationally Unstable Disk

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ABSTRACT

Core accretion and disk instability require giant protoplanets to form in the presence of disk gas. Protoplanet migration models generally assume disk masses low enough that the disk's self-gravity can be neglected. However, disk instability requires a disk massive enough to be marginally gravitationally unstable (MGU). Even for core accretion, a FU Orionis outburst may require a brief MGU disk phase. We present a new set of three dimensional, gravitational radiation hydrodynamics models of MGU disks with multiple protoplanets, which interact gravitationally with the disk and with each other, including disk gas mass accretion. Initial protoplanet masses are 0.01 to 10 $M_\oplus$ for core accretion models, and 0.1 to 3 M_{Jup} for Nice scenario models, starting on circular orbits with radii of 6, 8, 10, or 12 AU, inside a 0.091 $M_\odot$ disk extending from 4 to 20 AU around a $1 M_\odot$ protostar. Evolutions are followed for up to ~ 4000 yr and involve phases of relative stability ($e \sim 0.1$) interspersed with chaotic phases ($e \sim 0.4$) of orbital interchanges. The 0.01 to 10 $M_\oplus$ cores can orbit stably for ~ 1000 yr: monotonic inward or outward orbital migration of the type seen in low mass disks does not occur. A system with giant planet masses similar to our Solar System (1.0, 0.33, 0.1, 0.1 M_{Jup}) was stable for over 1000 yr, and a Jupiter-Saturn-like system was stable for over 3800 yr, implying that our giant planets might well survive a MGU disk phase.

Subject headings: Hydrodynamics – Protoplanetary disks – Planet-disk interactions – Planets and satellites: dynamical evolution and stability – Planets and satellites: formation

1. Introduction

The discovery of short-period giant planets forced theorists to study inward orbital migration of giant planets formed at much greater distances. Attention has focused on Type I and Type II migration (Kley & Nelson 2012), the former dealing with $\sim 10 M_\oplus$ cores that migrate rapidly due to tidal torques with the gaseous disk, and the latter dealing with $\sim M_{Jup}$ protoplanets that are massive enough to open a gap in the disk, and thereafter evolve along with the disk. Unchecked inward Type I migration presumably can lead to a loss of the protoplanet. However, in the core accretion scenario for giant planet formation, inward Type I migration can speed the growth of a core by the sweeping up of the smaller bodies it encounters (e.g., Alibert et al. 2005), albeit at the price of a free parameter that reduces the Type I migration rate to a favorable value. Most Type I migration models consider disks with masses low enough that the disk's self-gravity can be ignored. However, analytical (Pierens & Huré 2005) and two-dimenensional hydrodynamical (Baruteau & Masset 2008) studies of Type I migration in self-gravitating disks found that the inclusion of disk self-gravity could lead to a significant reduction in the Type I migration rate. Similarly, Nelson & Benz (2003) found that even massive planets undergoing Type I migration in gravitationally stable disks had their migration rates reduced when the disk's self-gravity was included. Disk instability scenarios for giant planet formation in self-gravitating disks may sidestep the danger of Type I migration, as the clumps initially formed have masses of order 1 M_{Jup} (e.g., Boss 2005), large enough to open disk gaps and undergo Type II migration in a low mass disk.

Marginally gravitationally unstable (MGU) disks are of interest from several points of view. Solar-type young stars are observed to undergo FU Orionis outbursts (e.g., Hartmann & Kenyon 1996), where mass accretion rates onto the central protostar increase dramatically and remain high for periods of order 100 yr. Such outbursts may well occur every $\sim 10^4$ yr in T Tauri stars. A leading explanation for FU Orionis outbursts is a MGU disk (e.g., Zhu et al. 2010; Vorobyov & Basu 2010). MGU disks also offer an attractive mechanism for achieving the large-scale transport, both inward and outward, of small particles in the solar nebula that appears to be required to explain the presence of refractory grains in comets (e.g., Brownlee et al. 2006; Boss et al. 2012), and for mixing initially spatially heterogeneous distributions of isotopes (Boss 2012a). Finally, MGU disks are required for the disk instability mechanism of giant planet formation to operate (e.g., Boss 1997). Recent extremely high spatial resolution models have shown that disk instability is able to produce fragments (even inside ~ 10 AU) in MGU disks with much longer cooling times than had previously been thought to be needed (Pardekooper 2012; Meru & Bate 2012), in strong support of the disk instability mechanism.

Core accretion and disk instability both require giant protoplanets to form in the presence of the disk gas. Considerable efforts have gone into theoretical studies of protoplanetary

orbital migration (reviewed by Kley & Nelson 2012), yet nearly all models of the interactions of protoplanets with disk gas assume a disk mass low enough that the disk's self-gravity can be neglected, as previously noted. The exceptions also include works by Boss (2005), Baruteau et al. (2011), and Michael et al. (2011), who all studied quite different initial conditions for MGU disks, and as a result found a wide range of outcomes, from large-scale inward orbital migration, to relatively little orbital migration.

The Nice model has become a leading explanation for the orbital evolution of the giant planets in our solar system (Tsiganis et al. 2005; Gomes et al. 2005; Levison et al. 2008). In the Nice model, Saturn forms with an orbital period less than twice that of Jupiter, but as both planets interact with a massive residual disk of planetesimals (following dissipation of the gaseous disk), their orbits cross a 2:1 mean motion resonance, where Saturn's orbital period equals twice that of Jupiter. At that point, their orbits are destabilized, and Saturn undergoes a phase of close encounters with Uranus and Neptune, which are assumed to have formed outside Saturn's orbit. The two ice giants are kicked further outward to their present orbits, while the two gas giants are left behind on slightly eccentric orbits, with $e \sim 0.05$ to 0.1. While the Nice model was derived in the context of the core accretion model for giant planet formation, the question arises as to the orbital stability of multiple giant planet systems during a MGU phase, such as during a FU Orionis outburst prior to gaseous disk dissipation in the core accretion scenario, or as a result of formation by the disk instability mechanism.

Boss (2005) studied the orbital evolution of single "virtual protoplanets" (VP) with initial masses of 1 M_{Jup} embedded in a MGU disk. Here we present two new set of models, each with up to four VPs initially present in the MGU disk. In the first set, the VP masses are chosen to investigate the orbital evolution of $\sim$ Earth-mass cores trying to accrete gas during an MGU disk phase, and in the second set, to investigate the evolution of already formed giant planets embedded in MGU disks, a situation analogous to the Nice model of giant planet evolution in gas-free, massive planetesimal disks.

2. Numerical Methods for the Disk

The three dimensional (3D) numerical hydrodynamics code used is the same as that used in previous studies of disk instability (e.g., Boss 2005, 2010, 2011, 2012b), any one of which may be consulted for a brief summary of the numerical techniques. A full description of the code and various test cases is given by Boss & Myhill (1992). The code has been also been tested specifically for accuracy in disk instability calculations (e.g., Boss 2012b, and references therein).

Compared to the models presented by Boss (2005), the only differences are that the equations were solved on a spherical coordinate grid with $N_\phi = 256$ and the number of terms in the spherical harmonic expansion for the gravitational potential of the disk was $N_{Ylm} = 32$. As in Boss (2005), the equations were solved with $N_r = 101$ and $N_\theta = 23$ in $\pi/2 \geq \theta \geq 0$. The radial grid was uniformly spaced with $\Delta r = 0.16$ AU between 4 AU and 20 AU. The θ grid was compressed into the midplane to ensure adequate vertical resolution ($\Delta\theta = 0.3^o$ at the midplane). While this spatial resolution is sufficient to model the large-scale evolution of a MGU disk, it may not be fine enough to properly resolve the Roche lobes and Hill spheres of individual protoplanets. However, given that the masses of the even the most massive protoplanets that form are much less than the total disk mass, to first order MGU disks evolve on their own, with only minor perturbations from the embedded protoplanets. In fact, searches for features in the disk gas distribution associated with the more massive protoplanets did not reveal any clear structures.

The Jeans length criterion (e.g., Truelove et al. 1997; Boss 2002) was used to ensure that any clumps that formed were not numerical artifacts during the 400 yr of disk evolution leading from the analytical initial conditions (see below) to the relaxed disk phase when the protoplanets were inserted into the models. In the interests of pushing the protoplanet models as far as possible in time, however, the Jeans length criterion was thereafter ignored, as it might at times have forced a significant refinement in the grid structure, slowing the subsequent evolution. This approach seemed reasonable, as studying any subsequent clump formation was not the goal of these models. Even still, the models typically required from two to three years of continual computation on a dedicated cluster node.

3. Initial Conditions for the Disk

The MGU disk system initially consists of a $1 M_\odot$ central protostar surrounded by a protoplanetary disk with a mass of 0.091 $M_\odot$ between 4 AU and 20 AU. The initial protoplanetary disk structure is the same as that defined in Boss (2005), which is an an approximate vertical density distribution (Boss 1993) for an adiabatic, self-gravitating disk of arbitrary thickness in near-Keplerian rotation about a point mass M_s

$$\rho(R,Z)^{\gamma-1} = \rho_o(R)^{\gamma-1}$$
$$-\Big(\frac{\gamma-1}{\gamma}\Big)\Big[\Big(\frac{2\pi G\sigma(R)}{K}\Big)Z + \frac{GM_s}{K}\Big(\frac{1}{R} - \frac{1}{(R^2+Z^2)^{1/2}}\Big)\Big],$$

where R and Z are cylindrical coordinates, $\rho_o(R)$ is the midplane density, and $\sigma(R)$ is the

surface density. The adiabatic pressure used in the initial model is defined by $p = K\rho^\gamma$, where the adiabatic constant $K = 1.7 \times 10^{17}$ (cgs units) and $\gamma = 5/3$ for the initial model. The radial variation of the midplane density is a power law that ensures near-Keplerian rotation throughout the disk

$$\rho_o(R) = \rho_{o4}\left(\frac{R_4}{R}\right)^{3/2},$$

where $\rho_{o4} = 1.0 \times 10^{-10}$ g cm^{-3} and $R_4 = 4$ AU. A lower density halo ρ_h of infalling molecular cloud gas and dust surrounds the disk, with

$$\rho_h(r) = \rho_{h4}\left(\frac{R_4}{r}\right)^{3/2},$$

where $\rho_{h4} = 1.0 \times 10^{-14}$ g cm^{-3}, and r is the spherical coordinate radius.

The initial temperature profile is based on the two dimensional radiative hydrodynamics calculations of Boss (1996), specifically the "standard model" shown in Figure 9 of Boss (1996). The models have an outer disk temperature of $T_o = 50$ K, resulting in an initial Q gravitational stability parameter as low as $Q_{min} = 1.5$ in the outermost disk, so that the outermost disk is gravitationally unstable. The initial midplane disk temperature at 4 AU (the inner boundary) is 600 K, leading to $Q > 10$ in the innermost disk and gravitational stability. Overall, then, the disk is marginally gravitationally unstable. The initial disk model is then evolved for 400 yr (3.8×10^5 time steps) before the protoplanets are inserted into the disk, in order to allow the disk to settle into a steady phase of disk instability, as shown in Figure 1. Several distinct clumps and spiral arms are evident at this initial time for the protoplanet evolutions, allowing the models to investigate a "worst case scenario" for the survival of protoplanets during an MGU disk phase.

4. Numerical Methods for the Protoplanets

The protoplanets are handled in the same manner as described by Boss (2005), where a dense clump was represented by a virtual protoplanet (VP) in the dynamically evolving disk. A VP is a point mass object that accretes mass and angular momentum from the disk, thereby determining its orbital evolution, subject to the gravitational forces of the central protostar and the spiral arms and clumps of the MGU disk, while the disk itself reacts to the gravitational force of the virtual protoplanet (VP). Rice et al. (2003) used a similar technique in their smoothed particle hydrodynamics (SPH) models of fragmentation

in protostellar disks. Krumholz et al. (2004) described their own technique for inserting sink particles into an adaptive mesh refinement hydrodynamics code.

Each VP is assumed to accrete mass $\dot{M}$ at the rate given by the Bondi-Hoyle-Lyttleton (BHL) formula (Livio 1986; Ruffert & Arnett 1994)

$$\dot{M} = \frac{f 4\pi\rho(GM)^2}{(v^2 + c_s^2)^{3/2}},$$

where f is a dimensionless coefficient, G is the gravitational constant, M is the VP mass, ρ is the local disk gas density, c_s is the local sound speed, and v is the speed of the VP through the local gas. The VPs also accrete orbital angular momentum from the disk gas, by accreting an amount of momentum from the local hydrodynamical cell proportional to the mass being accreted from that cell, i.e., by "consistent advection", in such a way as to guarantee the conservation of the total orbital angular momentum of the entire system. The mass and angular momentum accreted by each VP are removed from the cells in which they reside during the time step under consideration.

The protoplanets' resulting updated velocity is used to calculate their updated positions, to second-order accuracy in space and time, consistent with the accuracy of the hydrodynamical solution. To keep the system synchronized, the same time step is used for both the disk hydrodynamics and the protoplanet orbital evolutions. The hydrodynamical time steps used are quite small, typically $< 10^{-3}$ yr. This is about 10^{-4} of an orbital period at 4 AU, and about 10^{-5} of an orbital period at 20 AU. These exceedingly small time steps help to ensure the accuracy of the protoplanets' orbital evolutions; symplectic integrators typically achieve excellent energy conservation when using time steps of order 10^{-3} the orbital period (e.g., Chambers 2003).

As in Boss (2005), the VPs affect the disk's evolution through having the gravitational potentials of each of the point masses ($-GM/R$) added into the total gravitational potential of the entire system, where the radius R is the distance from a VP position to a cell center. This radius R is constrained to be no smaller than $\Delta r/2$, where Δr is the local grid spacing in the radial coordinate of the hydrodynamical grid, thereby softening the gravitational potential in order to avoid singularities when a VP approaches the center of a grid cell. The VPs evolve as a result of the mass and angular momentum accreted, subject to the gravitational potential of the protostar and disk, as well as to the effects of centrifugal force. Gas drag is neglected, as is appropriate for these relatively massive protoplanets (cf. Boss et al. 2012, where gas drag is included for small particles evolving in MGU disks). Numerical tests with $\dot{M} = 0$ and the gravitational potential of only a central protostar (Boss 2005) showed that VPs on initially circular or elliptical orbits with semimajor axes of 5 AU orbit

stably for at least 500 years, with the VP's angular momentum being conserved to at least 8 digits.

5. Initial Conditions for the Protoplanets

For the $\sim$ Earth-mass protoplanet models, all four models were initialized in the same manner, with the only variation being in the initial mass of the protoplanet, as follows: model a: 0.01 $M_\oplus$, model b: 0.10 $M_\oplus$, model c: 1.0 $M_\oplus$, and model d: 10.0 $M_\oplus$. In each case, four initially equal mass protoplanets were inserted in the midplane locations denoted in Figure 1, at orbital radii of 6 AU, 8 AU, 10 AU, and 12 AU, respectively, with the variations in azimuthal locations evident in Figure 1. Each protoplanet was inserted at the center of a hydrodynamical cell with the same radial and azimuthal velocity as that of the disk gas in that cell. Because the hydrodynamical grid is restricted to the top hemisphere ($\pi/2 \geq \theta \geq 0$) of the spherical coordinate grid, the protoplanets must be limited to orbiting in the disk midplane. The $\sim$ Earth-mass models were allowed to accrete mass according to the BHL formula with $f = 10^{-4}$ being a factor in the formula. Nelson & Benz (2003) explored a range of values of f, from 1 to 10^{-4}. The coefficient f should be less than unity because of various effects neglected in the analysis, such as the accretion of rotating gas of nonuniform density and temperature, shock fronts, and other effects as well, such as three dimensionality (e.g., Krumholz et al. 2005; Blondin & Raymer 2012). Krumholz et al. (2005) found that f could be as low as 10^{-2} purely as a result of the vorticity of the gas being accreted.

Table 1 summarizes the initial conditions and outcomes for the $\sim$ Earth-mass protoplanets, while Tables 2 and 3 show the same information for the giant protoplanet models, starting with VP masses in the range of 0.1 M_{Jup} to 3 M_{Jup}, again at initial distances of 6 AU, 8 AU, 10 AU, or 12 AU from the protostar. These models were run with either $f = 10^{-4}$ or 10^{-3} in the BHL mass accretion formula. Also shown in all three tables are the final masses of the protoplanets (M_f) at the final time (t_f) for the protoplanets that were still between 4 AU and 20 AU at the end of the calculation. Protoplanets that hit either the inner or the outer boundary are noted as having been ejected "in" or "out", respectively. Note that close encounters between the protoplanets need not lead to "ejections", so long as the planet manages to stay between 4 AU and 20 AU. Similarly, not all ejections need be the immediate result of a close encounter – further interactions with the massive disk can also result in a protoplanet hitting either the inner or outer disk boundary. In any case, these ejections do not mean that the ejected protoplanet has received enough of a kinetic energy increase to reach the escape speed from the protostar and protoplanetary disk system. In fact, because

of the softening of the gravitational potential of the protoplanets, close encounters between protoplanets cannot have effectively closer approaches than $\Delta r/2 = 0.08$ AU, and so cannot lead to protoplanets that reach the escape speed, which would require closer approaches at least ten times smaller. The models also do not include the effects of extended atmospheres around the protoplanets, which could play a role in very close encounters. Finally, the tables also list the amount of disk mass that was accreted by the central protostar during the evolutions, ΔM_s.

6. Results

6.1. Earth-Mass Protoplanets

We first consider the possible fates of $\sim$ Earth-mass cores that are attempting to accrete gas and become giant planets during a MGU disk phase. This question has not been considered to date in the context of the classic core accretion scenario, where the disk mass is assumed to be low enough to preclude gravitational instability (e.g., Hubickyj et al. 2005; Lissauer et al. 2009)

Figures 2 and 3 show the evolutions of the four $\sim$ Earth-mass protoplanet models. Monotonically inward migration of the type associated with Type I migration is not seen. In general, the protoplanets experienced a significant amount of orbital perturbations driven by the clumps and spiral arms in the MGU disk, resulting in continually evolving, quasi-periodic changes in the orbital semimajor axes and eccentricities. The time scales for these quasi-periodic wobbles in a and e are of order $\sim$ 30 yr, i.e., the orbital period at a distance of order $\sim$ 10 AU, where the MGU disk is most active at forming transient clumps and spiral arms (Figure 1). While vigorous, these perturbations tend to average out to result in little net overall migration of the cores. Nevertheless, in each of the four models, at least one core was perturbed enough to hit either the 4 AU or the 20 AU disk boundary; nearly half (7/16) of the cores were considered to be "ejected" in these models (Table 1). Note that this relatively large fraction of "ejected" cores is in reality a severe overestimate, as in a more realistic disk model, cores would not be considered lost unless they collided with the central protostar, or were physically ejected from the system on hyperbolic orbits. Given this caveat, the models depicted in Figure 2 show that $\sim$ Earth-mass cores should be able to survive a brief ($\sim 10^3$ yr) MGU phase of the sort associated with FU Orionis outbursts, though a few cores might undergo large excursions in semimajor axis as a result, and the surviving cores are likely to be left on significantly eccentric ($e \sim 0.3$) orbits (Figure 3). These results are relatively independent of the initial core mass: all four models shown in Figures 2 and 3 appear qualitatively similar.

Because the Earth-mass models all assumed $f = 10^{-4}$ for BHL mass accretion, and because all started off with relatively small masses, the amount of mass accreted during the $\sim 10^3$ yr evolutions was negligible (Table 1); the largest increase was in model d, with initially 10 $M_\oplus$ protoplanets, where the amount of mass accreted by one of the protoplanets was $\sim 0.002 M_\oplus$.

6.2. Giant-Planet Mass Protoplanets

We now turn to the models motivated by the Nice scenario for the orbital evolution of the Solar System's giant planets (Tsiganis et al. 2005; Gomes et al. 2005; Levison et al. 2008). We seek to learn what might happen to massive gas and ice giant planets, formed by either core accretion or disk instability, if they should encounter a MGU disk phase, such as during an FU Orionis outburst.

Table 2 summarizes the Nice scenario models with two different values of the BHL gas accretion factor f. In model M, with $f = 10^{-4}$, an initially $1 M_{Jup}$ protoplanet gained $0.6 M_{Jup}$ in mass during 3400 yr, yielding a mass accretion rate of $\dot{M} \sim 2 \times 10^{-4} M_{Jup}$ yr^{-1}. In model Mh, with $f = 10^{-3}$, an initially $1 M_{Jup}$ protoplanet gained $1.5 M_{Jup}$ in mass during 1300 yr, yielding a mass accretion rate of $\sim 10^{-3} M_{Jup}$ yr^{-1}. The relatively high rate of mass accretion in model Mh may not be physically reasonable. Nelson & Benz (2003) argued that such rates should be less than $\sim 10^{-4} M_{Jup}$ yr^{-1}. Kley (1999) found $\dot{M} = 4.35 \times 10^{-5} M_{Jup}$ yr^{-1} in his standard model, while Machida et al. (2010) found $\dot{M} \sim 10^{-5} M_{Jup}$ yr^{-1} in their numerical simulations. However, in all of these other studies, the disks considered were not MGU disks, and hence the protoplanetary mass accretion rates could be expected to be significantly smaller. Nevertheless, the $\dot{M}$ estimates for models M and Mh imply that the models with $f = 10^{-4}$ are probably more realistic than those with $f = 10^{-3}$. The final masses listed in Table 2 show that the mass accretion rates are systematically considerably higher in the $f = 10^{-3}$ models than in those with $f = 10^{-4}$, as is to be expected.

Table 2 also shows that only 10 of the initial total of 32 protoplanets remained within the disk during the evolutions: 22 hit either the inner or outer boundary, 10 of the $f = 10^{-4}$ models, and 12 of the $f = 10^{-3}$ models. Considering the small number statistics, there does not appear to be a strong dependence on the assumed value of f. However, in the models with the most massive protoplanets (N, Nn), 7 out of 8 protoplanets were ejected, while 15 out of 24 were ejected in the lower mass models (M, Mh, O, Oh, P, Ph). Apparently protoplanets with initial masses of $\sim 3 M_{Jup}$ are more likely to undergo strong mutual close encounters, which, coupled with the MGU disk perturbations, eventually lead to their ejections. The higher overall ejection frequency for the Table 2 models compared to those in Table 1 is due

in part to the longer time periods calculated for the Table 2 models, with the remaining difference being caused by the stronger effects of close encounters between the much more massive protoplanets in the Table 2 models.

Figures 4 and 5 depict the semimajor axis evolutions of the eight models listed in Table 2. As in the case of the $\sim$ Earth-mass cores, the protoplanets are subjected to quasi-periodic perturbations from the MGU disk's clumps and spiral arms, resulting in somewhat chaotic orbital evolutions, but again without any clear evidence for monotonically inward (or outward) migration. In general, the semimajor axes of the surviving protoplanets remained in the range of $\sim$ 5 AU to $\sim$ 15 AU, similar to the initial orbits, in spite of mutual close encounters leading to frequent ejections of the less fortunate, generally lower mass, protoplanets.

Table 3 summarizes the models that are the closest to the Nice model for our Solar System, all calculated with the same value of $f = 10^{-4}$. The initial protoplanet masses in these models are closer to those of the current masses of the giant planets in our Solar System than those of the previous models. Model Q, in particular, has masses similar to those of Jupiter, Saturn, Uranus, and Neptune, though the 0.1 M_{Jup} protoplanets that represent the two ice giants start off with masses about twice that of Uranus and Neptune. Model R explores a situation with even more massive outer protoplanets, while models S and T investigate a system where only Jupiter and Saturn exist, starting at two different initial orbits for Saturn, 12 AU and 10 AU, respectively.

Figures 6 and 7 display the evolutions of the semimajor axes and eccentricities for the four models listed in Table 3. Model Q, the closest model to our outer Solar System, manages to survive intact for a period of at least 1200 yr, though only after undergoing a major orbital reshuffling: at the final time shown in Figure 6, the initially innermost Jupiter-mass protoplanet is now the outermost body, the initially Saturn-mass protoplanet is the innermost body, and the two initially outer ice giants are orbiting between the two gas giants, with all four having semimajor axes between $\sim$ 9 AU and $\sim$ 13 AU. Note the high eccentricities for prolonged periods for the two ice giant-mass protoplanets in models Q (Figure 7), implying that ejections are eventually likely for these bodies. These systems would presumably become even more unstable once the disk gas is removed, with an uncertain final outcome. A similar reordering of the orbital distribution occurs in model R, though in this case the initially 0.33 M_{Jup} protoplanet, and one of the 0.5 M_{Jup} protoplanets are ejected, leaving behind an outer 1.4 M_{Jup} gas giant and an inner 0.62 M_{Jup} protoplanet.

Model T shows that two gas giant planets can survive for $\sim$ 4000 yr in a MGU disk, though they may well interchange their orbital positions. On the other hand, with a different initial orbital configuration, model S shows that the initially Saturn-mass protoplanet might be ejected, leaving the initially Jupiter-mass protoplanet as the sole survivor after 3800 yr.

In both cases, the eccentricities of the protoplanets tend to be modest (Figure 7c,d), with $e \sim 0.05$ to 0.2.

7. Discussion

Tables 2 and 3 show that in a system with protoplanets of different initial masses, in nearly every case the protoplanet that is ejected is one of the lower mass protoplanets. The only exception to this general rule was the initially 1 M_{Jup} protoplanet in model Ph, which was ejected along with an initially 0.5 M_{Jup} protoplanet. Note, however, that even in this case, because of the high value of $f = 10^{-3}$, the two other initially 0.5 M_{Jup} protoplanets grew to masses of 2.6 M_{Jup} and 1.6 M_{Jup} by the end of the calculation, and these were the bodies responsible for ejecting the initially 1 M_{Jup} protoplanet. Hence the general rule appears to be that the more massive protoplanets are left behind during close orbital encounters, as is expected to be the case based on equipartition of energy: the less massive body will receive a larger velocity perturbation than the more massive body, and so is more likely to hit a disk boundary.

We now briefly compare the results to those of the previous studies of orbital migration in MGU disks. Boss (2005) considered the evolution of fully three dimensional MGU disks with a mass of 0.091 $M_\odot$ extending from 4 AU to 20 AU around a 1 $M_\odot$ protostar, i.e., the same situation as is considered here with multiple protoplanets with varied masses. Jupiter-mass protoplanets inserted at 8 AU were found by Boss (2005) to orbit fairly stably, or to move out to $\sim$ 10 AU, over $\sim 10^3$ yr, even while gaining mass by accretion. This implied that protoplanets in MGU disks do not immediately open disk gaps and undergo Type II migration. These results are quite consistent with the present models, where the addition of other protoplanets does not prevent the surviving protoplanets from orbiting relatively stably.

Baruteau et al. (2011) considered the evolution of two dimensional, thin MGU disks with a mass of 0.4 $M_\odot$ extending from 20 AU to 250 AU around a 1 $M_\odot$ protostar. Saturn-mass and Jupiter-mass protoplanets inserted at 100 AU were found to migrate rapidly inward to $\sim$ 25 AU, on a time scale comparable to that expected for Type I migration, $\sim 10^4$ yr, while planets with $5 M_{Jup}$ migrated even faster, in $\sim 3 \times 10^3$ yr. Type II migration did not occur, as the planets were unable to open disk gaps. The MGU nature of the evolving disk resulted in periodic outward motions, rather than the monotonic inward motions of classic Type I migration. These results are in basic agreement with the present models. Baruteau et al. (2011) included the effects of the planet's gravity on the disks, but did not include planet mass accretion (i.e., they fixed the planet masses), and their models were restricted

to considering the evolution of a single planet at a time, unlike the present models, where planet-planet interactions are an important factor. Most importantly, the Baruteau et al. (2011) models were limited to orbits in the outer disk: their planets were forced to stop inward migration at $\sim$ 25 AU, whereas the present models have protoplanets that start inside 12 AU. The absence of inward migration in the present models appears to be linked to the high inner disk temperatures ($\sim$ 600 K), leading to $Q >> 1$, and stifling to some extent the spiral arms just outside 4 AU (Figure 1), combined with the chaotic outcomes of protoplanet interactions with a MGU disk.

Michael et al. (2011) considered the evolution of fully three dimensional MGU disks with a mass of 0.14 $M_\odot$ extending from 5 AU to 40 AU around a 1 $M_\odot$ protostar. Two Jupiter-mass protoplanets inserted at 25 AU were found to migrate rapidly inward to $\sim$ 17 AU in $\sim 10^3$ yr, where both stalled. The inward motion was again not monotonic, but rather jerky, due to the MGU disk interactions. Similar to Baruteau et al. (2011), Michael et al. (2011) included the effects of the planet's gravity on the disk, did not include planetary mass accretion, and calculated evolutions for only a single planet at a time. Michael et al. (2011) also studied considerably larger disks than the present models, but their inner disk boundary of 5 AU was quite similar to the 4 AU value in the present models. The Michael et al. (2011) protoplanets migrated inward but stopped at $\sim$ 17 AU, whereas in the present models, the survivors clustered around distances of $\sim$ 8 AU to $\sim$ 13 AU. This slight difference in outcomes can be attributed to the different underlying MGU disk structures used in the two sets of models: Michael et al. (2011) started with a disk with a minimum $Q = 1.38$ at 26.7 AU, whereas in the present models, the minimum $Q = 1.5$ occurred at the outer disk boundary (20 AU), and rose to $Q > 10$ in the inner disk. Given these MGU disk differences, the Michael et al. (2011) results seem to be compatible with the present results.

Finally, throughout the evolutions of all of these MGU disk models, disk mass flowed freely inward, past the orbiting protoplanets, and was accreted by the inner grid boundary at 4 AU. The total amount of mass accreted by the central region (i.e., the protostar) was typically $\sim 0.03 M_\odot$ (Tables 1, 2, 3) over a time period of $\sim$ 3000 yrs, leading to a protostellar mass accretion rate of $\sim 10^{-5} M_\odot$ yr^{-1}. This rate is comparable to the inferred mass accretion rates for T Tauri stars undergoing FU Orionis outbursts (e.g., Hartmann & Kenyon 1996), confirming the applicability of these MGU disk models for protoplanetary systems undergoing FU Orionis events. The Tables show that this central mass accretion rate did not vary significantly across the models calculated, showing that the varied protoplanet masses had little effect on the overall evolution of the MGU disks.

8. Conclusions

Given the limited number of models run, and the resulting highly incomplete examination of the initial conditions parameter space, one cannot draw too strong of a conclusion from these models, but at the least, these models illustrate the range of outcomes that could result from a MGU disk phase during planetary system formation. Neverthless, it is clear that a MGU disk phase need not be fatal to growing cores in the core accretion scenario, or to giant planets formed by either core accretion or disk instability, at least not for protoplanets with initial orbits in the range of 6 AU to 12 AU from a solar-mass protostar. FU Orionis phases thus need not be fatal to the giant planet formation process. It is even conceivable that a Nice model-like scenario could be constructed for protoplanets that survive a MGU disk phase, though the most Nice-like model presented here (model Q) ended up with Jupiter as the outermost body, rather than the innermost. Other initial conditions might well lead to a more Nice-like outcome.

The $\sim$ Earth-mass protoplanets are excited to relatively high eccentricity orbits during the MGU disk phase, with $e \sim 0.2$ to 0.5. For the giant-planet-mass models, the final eccentricities are more modest, typically with $e \sim 0.05$ to 0.2, as is to be expected on the basis of equipartition of energy. Hence, except for limited periods of time, the orbital eccentricities for the giant planets are not as high as the highest values observed for Doppler-discovered extrasolar giant planets, where values as high as $e \sim 0.8$ have been determined. However, most exoplanets have more modest eccentricities, with over half having $e < 0.2$. The highest eccentricities found for exoplanets presumably have their origins in planet-planet scattering events, which can also result in significant orbital inclinations, and even in retrograde orbital rotations, which seems to be required in order to explain the orbital inclinations deduced on the basis of the Rossiter-McLaughlin effect for short-period exoplanets (e.g., Albrecht et al. 2012). The present models cannot address this possibility, as their limitation to protoplanet orbits within the disk midplane precludes interactions leading to inclined orbits.

As Boss (2005) found, protoplanets located at $\sim$ 10 AU in a MGU disk can orbit relatively stably for significant periods of time ($\sim 10^3$ yr or more), without undergoing monotonic inward Type-I-like migration, and without opening a disk gap, leading to Type-II-like migration. Instead, the quasi-periodic gravitational perturbations induced by the spiral arms and clumps of the MGU disk result in eccentric orbits ($e \sim 0.2$), while close encounters with the other protoplanets, combined with the MGU disk interactions, can lead to a significant number of "ejections" of the less massive protoplanets through hitting the inner or outer disk boundaries, though these "ejections" might very well be ameliorated in models that included a disk that extended from the true surface of the protostar ($\sim$ 0.05 AU) out to much larger distances ($\sim$ 50 AU). Such improved models of protoplanet-MGU disk

interactions are needed to determine if observed exoplanets on distant orbits (e.g., around HR 8799; Marois et al. 2008, 2010) could have formed closer to their star and then been ejected outward, or were formed more or less *in situ* (e.g., Boss 2011). Virtual protoplanet models based on the 60 AU-radius disk models of Boss (2011) are in progress and will be the subject of a future report.

I thank Hal Levison for suggesting in 2007 the Nice model calculations at the Nobel Symposium #135, John Chambers for advice on orbital fitting procedures, Sandy Keiser for her invaluable assistance with the Carnegie Alpha Cluster, and the referee for numerous suggestions for improving the paper. This research was supported in part by the NASA Origins of Solar Systems Program (NNX09AF62G) and contributed in part to the NASA Astrobiology Institute (NNA09DA81A). The calculations were performed on the Carnegie Alpha Cluster, the purchase of which was partially supported by NSF Major Research Instrumentation grant MRI-9976645.

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Table 1. Initial conditions and final outcomes for the $\sim$ Earth-mass protoplanets embedded in MGU disks with identical f BHL factors. M_i and a_i are the initial planet mass and orbital radius, M_f is the planet mass at the final time t_f, and $\Delta M_s/M_\odot$ is the amount of disk mass accreted by the central protostar by the end of the evolution.

model	f	$M_i/M_\oplus$	a_i (AU)	t_f (yr)	$M_f/M_\oplus$	$\Delta M_s/M_\odot$
a	10^{-4}	0.01	6	730	0.01	0.023
	"	0.01	8	"	0.01	"
	"	0.01	10	"	eject out	"
	"	0.01	12	"	0.01	"
b	10^{-4}	0.1	6	900	eject in	0.029
	"	0.1	8	"	eject in	"
	"	0.1	10	"	0.1	"
	"	0.1	12	"	0.1	"
c	10^{-4}	1.0	6	730	1.0	0.025
	"	1.0	8	"	eject in	"
	"	1.0	10	"	eject out	"
	"	1.0	12	"	1.0	"
d	10^{-4}	10.0	6	760	10.0	0.025
	"	10.0	8	"	eject out	"
	"	10.0	10	"	eject out	"
	"	10.0	12	"	10.0	"

Table 2. Initial conditions and final outcomes for the giant protoplanets embedded in MGU disks with varied f BHL factors.

model	f	M_i/M_{Jup}	a_i (AU)	t_f (yr)	M_f/M_{Jup}	$\Delta M_s/M_\odot$
M	10^{-4}	1.0	6	3400	1.6	0.028
	”	0.33	8	”	eject out	”
	”	0.33	10	”	eject out	”
	”	0.33	12	”	eject in	”
Mh	10^{-3}	1.0	6	1300	2.5	0.023
	”	0.33	8	”	eject out	”
	”	0.33	10	”	eject out	”
	”	0.33	12	”	eject out	”
N	10^{-4}	1.0	6	3400	eject out	0.042
	”	3.0	8	”	4.0	”
	”	3.0	10	”	eject out	”
	”	3.0	12	”	eject out	”
Nh	10^{-3}	1.0	6	410	eject out	0.019
	”	3.0	8	”	eject out	”
	”	3.0	10	”	eject in	”
	”	3.0	12	”	eject in	”
O	10^{-4}	1.0	6	3050	eject out	0.035
	”	1.0	8	”	eject in	”
	”	1.0	10	”	1.5	”
	”	1.0	12	”	1.1	”
Oh	10^{-3}	1.0	6	1080	eject out	0.023
	”	1.0	8	”	eject in	”
	”	1.0	10	”	3.1	”
	”	1.0	12	”	eject out	”
P	10^{-4}	1.0	6	3050	1.4	0.029
	”	0.5	8	”	eject out	”
	”	0.5	10	”	eject out	”
	”	0.5	12	”	0.91	”
Ph	10^{-3}	1.0	6	1500	eject out	0.024
	”	0.50	8	”	eject out	”
	”	0.50	10	”	2.6	”

Table 2—Continued

model	f	M_i/M_{Jup}	a_i (AU)	t_f (yr)	M_f/M_{Jup}	$\Delta M_s/M_\odot$
	”	0.50	12	”	1.6	”

Table 3. Initial conditions and final outcomes for the giant protoplanets embedded in MGU disks with identical f BHL factors.

model	f	M_i/M_{Jup}	a_i (AU)	t_f (yr)	M_f/M_{Jup}	$\Delta M_s/M_\odot$
Q	10^{-4}	1.0	6	1200	1.1	0.024
	”	0.33	8	”	0.37	”
	”	0.10	10	”	0.10	”
	”	0.10	12	”	0.10	”
R	10^{-4}	1.0	6	1200	1.4	0.022
	”	0.33	8	”	0.62	”
	”	0.50	10	”	eject in	”
	”	0.50	12	”	eject in	”
S	10^{-4}	1.0	6	3800	1.3	0.031
	”	0.33	12	”	eject in	”
T	10^{-4}	1.0	6	3800	1.3	0.029
	”	0.33	10	”	0.40	”

Fig. 1.— [Removed to fit within the limits for submission.] Midplane density contours for the MGU disk at the phase when the protoplanets (red circles) are first inserted into the models. The disk starts with a mass of $0.091 M_\odot$, with an outer radius of 20 AU and an inner radius of 4 AU, through which mass accretes onto the initially 1 $M_\odot$ central protostar. Density contours are shown in g cm^{-3}. Red circles denote the locations where protoplanets are inserted, at distances of 6, 8, 10, or 12 AU from the protostar, starting at 9 o'clock and rotating counterclockwise, respectively.

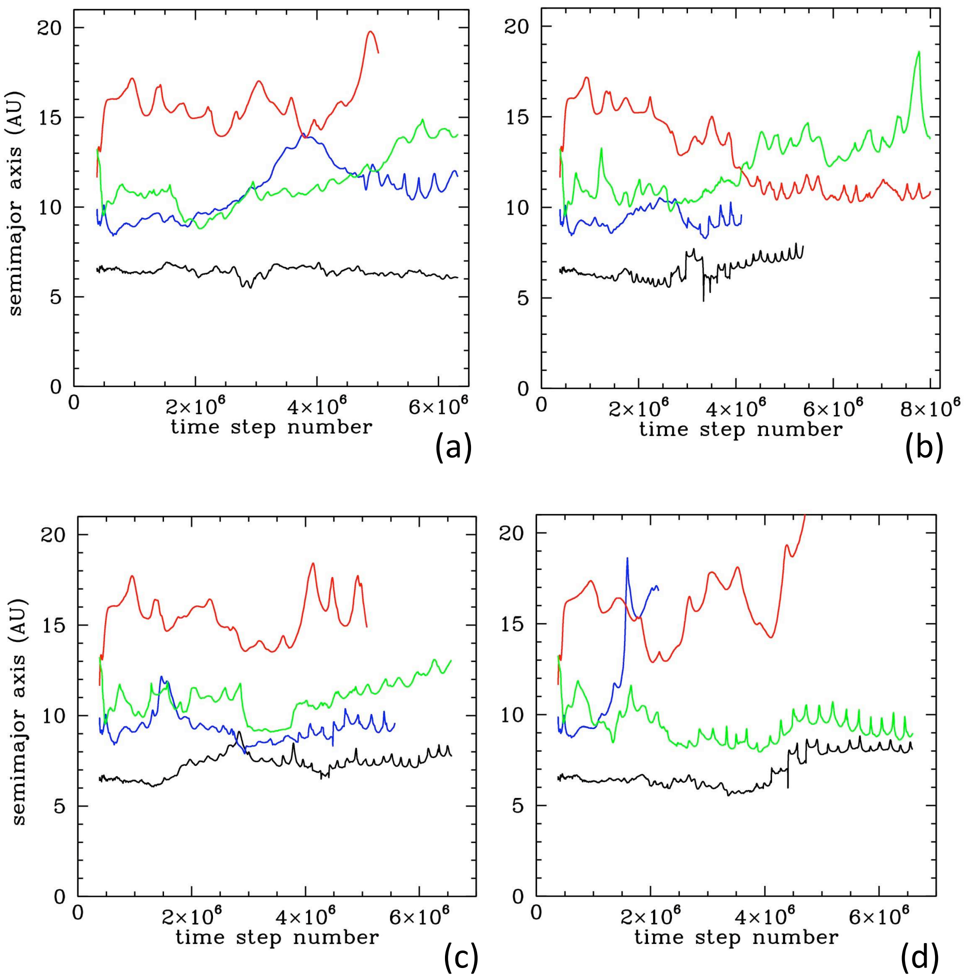

Fig. 2.— Time evolution of the semimajor axes of $\sim$ Earth-mass embedded protoplanets with initial masses of (a) 0.01 $M_\oplus$ (model a), (b) 0.10 $M_\oplus$ (model b), (c) 1.00 $M_\oplus$ (model c), and (d) 10.0 $M_\oplus$ (model d). Elapsed times since protoplanet insertion for each model are: (a) 730 yr, (b) 930 yr, (c) 730 yr, and (d) 760 yr. Data are plotted every 100 time steps. Protoplanets were inserted at radii of 6 AU (black), 8 AU (blue), 10 AU (red), or 12 AU (green), as shown in Figure 1. Protoplanets that strike the inner (4 AU) or outer (20 AU) disk boundaries are considered to be ejected and are dropped from the calculations.

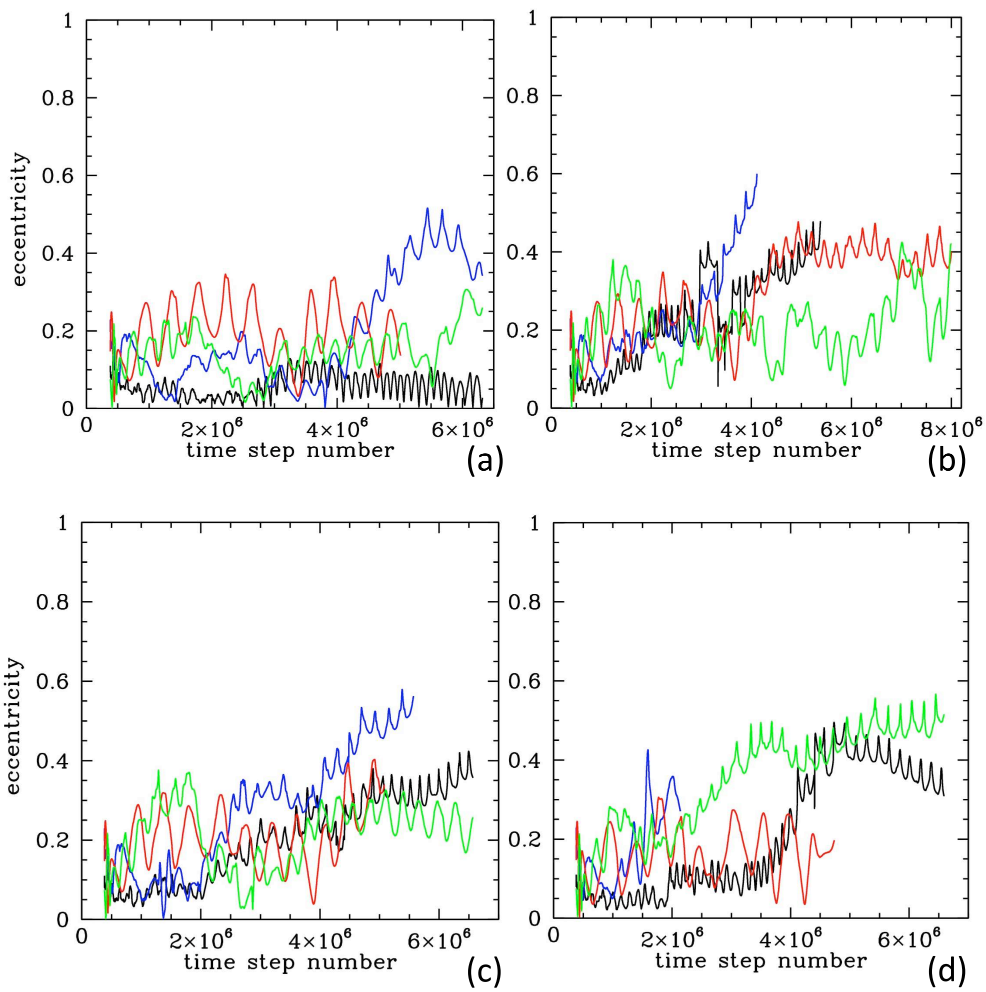

Fig. 3.— Time evolution of the eccentricities of $\sim$ Earth-mass embedded protoplanets, plotted in the same manner as in Figure 2, for models a, b, c, and d.

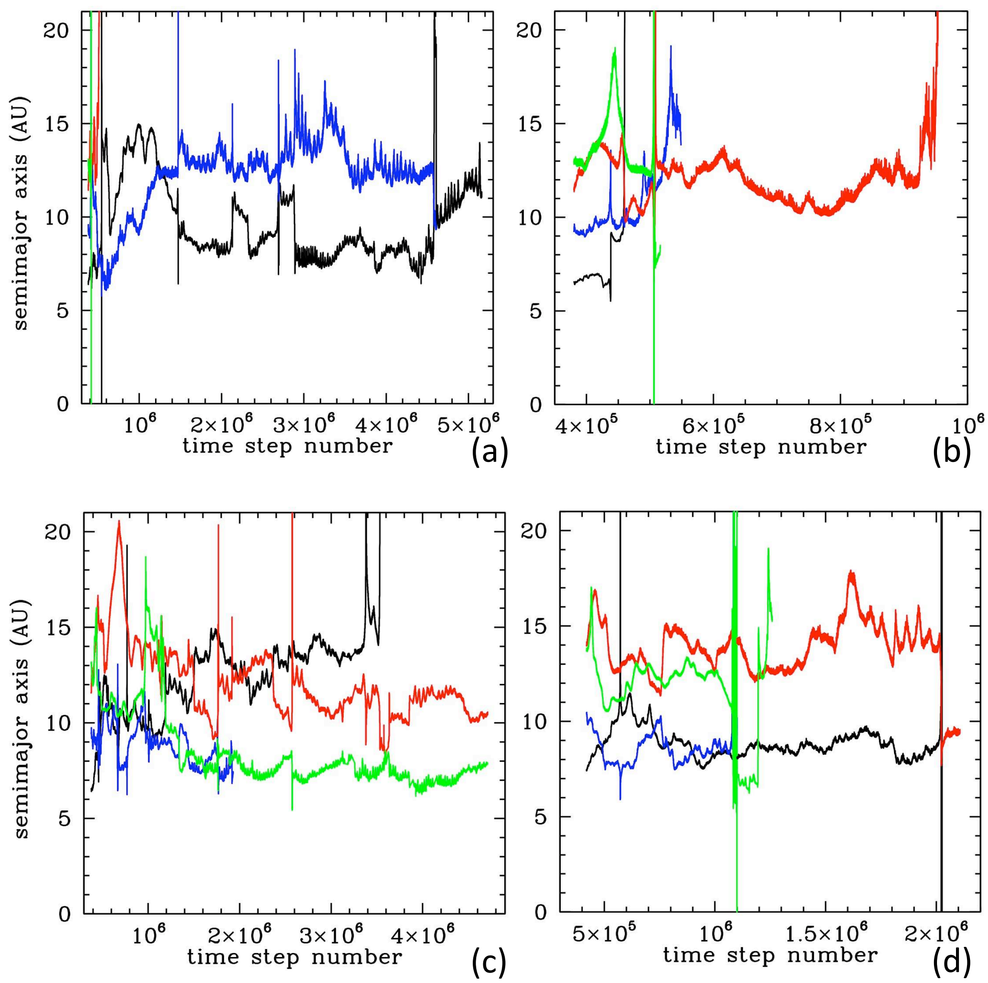

Fig. 4.— Time evolution of the semimajor axes of giant planet-mass embedded protoplanets, plotted as in Figure 2. Elapsed times: (a) model N: 3400 yr, (b) model Nh: 410 yr, (c) model O: 3050 yr, and (d) model Oh: 1080 yr.

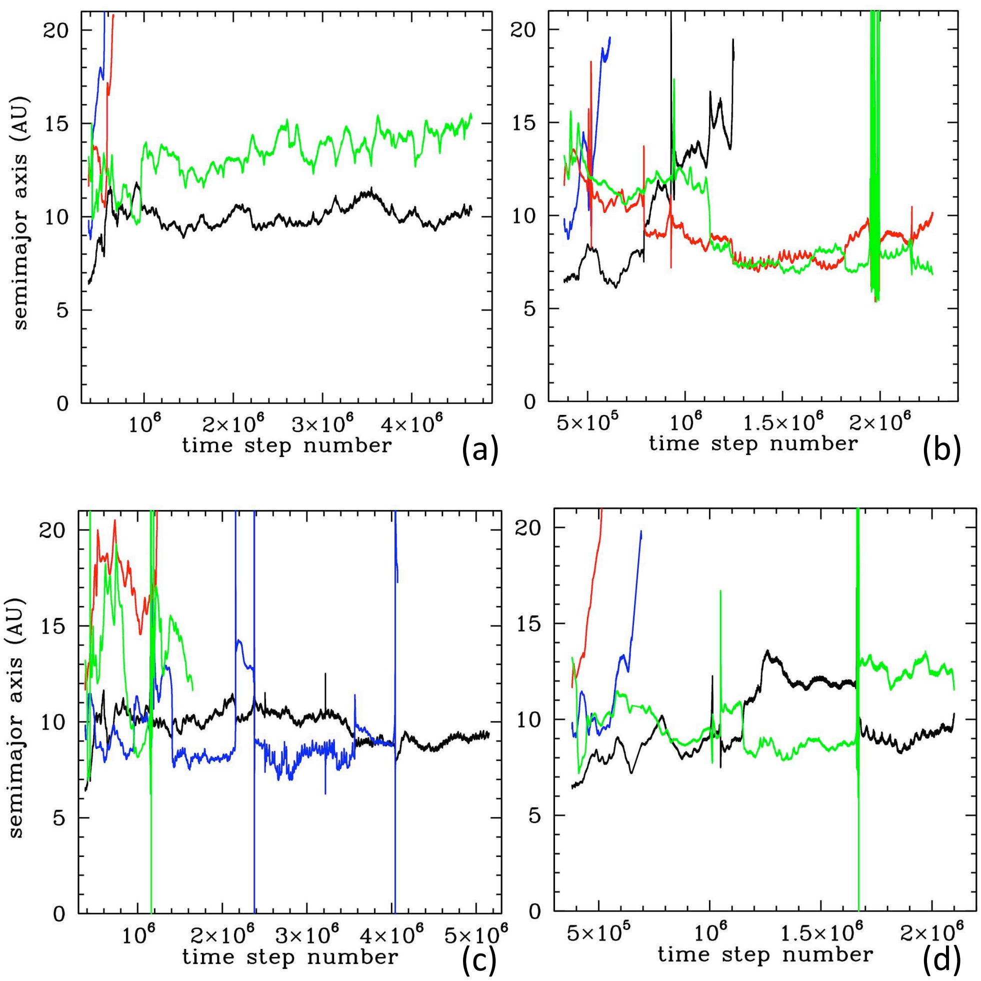

Fig. 5.— Time evolution of the semimajor axes of giant planet-mass embedded protoplanets, plotted as in Figure 2. Elapsed times: (a) model P: 3050 yr, (b) model Ph: 1500 yr, (c) model M: 3400 yr, and (d) model Mh: 1300 yr.

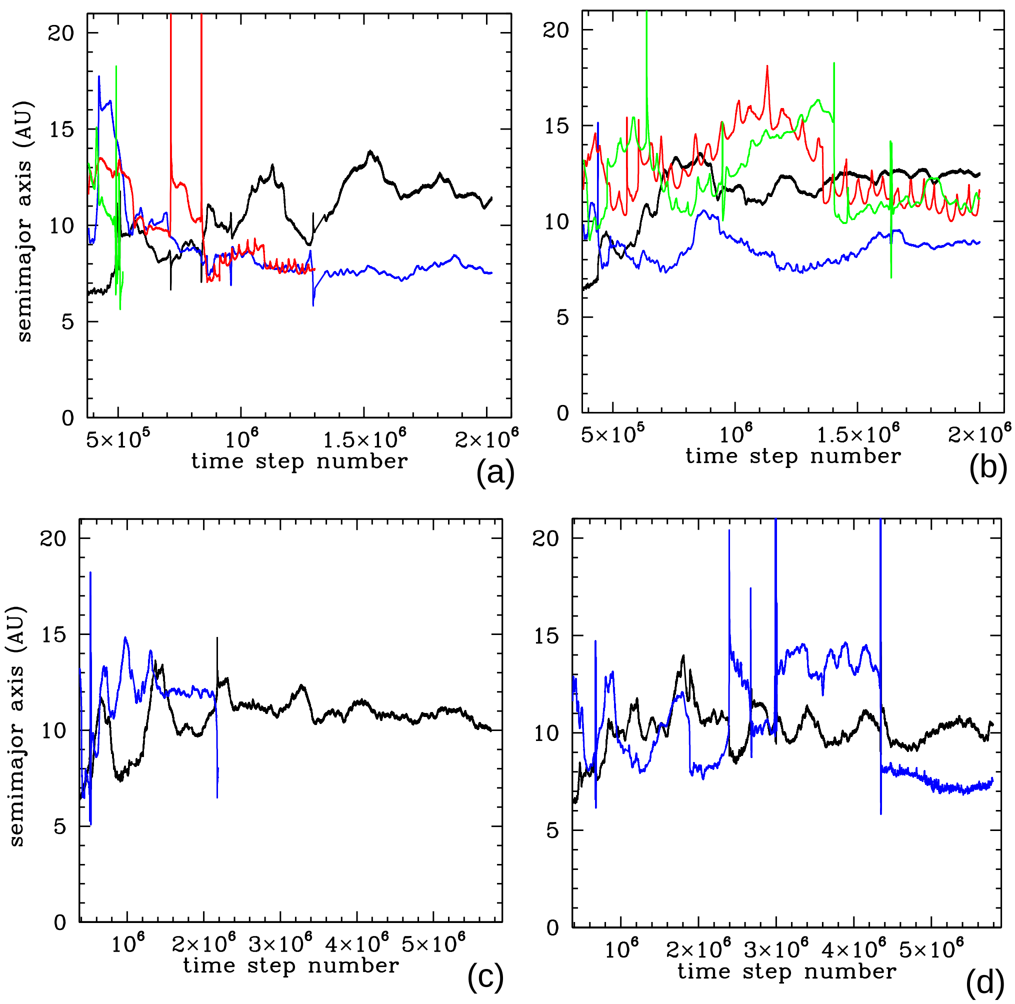

Fig. 6.— Time evolution of the semimajor axes of giant planet-mass embedded protoplanets, plotted as in Figure 2. Elapsed times: (a) model R: 1200 yr, (b) model Q: 1200 yr, (c) model S: 3800 yr, and (d) model T: 3800 yr.

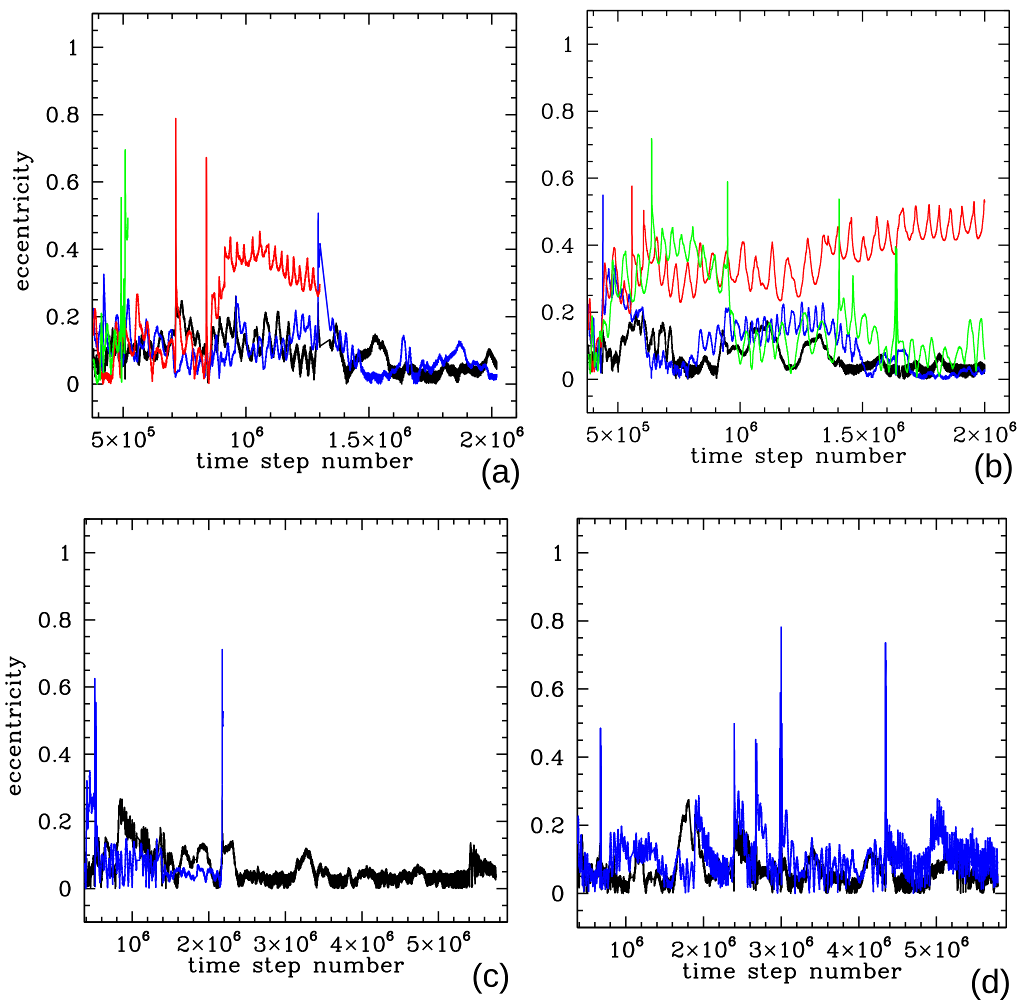

Fig. 7.— Time evolution of the eccentricities of giant planet-mass embedded protoplanets, plotted as in Figure 6. Elapsed times: (a) model R: 1200 yr, (b) model Q: 1200 yr, (c) model S: 3800 yr, and (d) model T: 3800 yr.